Environmental Wireless Sensor Network Deployment in Food Industry: from Theory to Practice

E. Quesada, M.V. Maigler, A. Barbado, J. Valverde, J. Portilla, T. Riesgo

I. Introduction

The huge differences between theoretical analysis and real environments make deployment planning a very difficult task. While most planning tools are focused on communications quality to calculate the appropriate number of nodes by modelling obstacles in the environment to maximize battery lifetime or optimize hardware costs, sensor placing and working conditions are still a pending subject.

General problems such as sensor soiling, , unreachable node locations and interaction with workers, together with the difficulty of selecting the proper sensors to measure environmental parameters while holding costs down and having in mind that they need to measure chemical species in an unattended way, is not yet covered by planning tools.

The main objective of this work is to present an environmental application of a WSN in the food industry together with all the real obstacles found both in the design and deployment processes.

This paper is organized as follows. Section II gives an overview of the different solutions that already exist in the state of the art. Section III describes the WSN platform. Section IV gives a brief environment description. Section V shows the main steps followed in the deployment related to communications. Section VI shows some problems found before and during the factory deployment and provides a deployment analysis related to the chosen sensors and Section VII finishes with some conclusions about this work.

II. State of Knowledge

Hundreds of references related to WSN applications can be found in the literature, but it is difficult to find real approaches and problems. In [1], three environmental monitoring domains are presented: terrestrial vegetation, animal movement and soil.

Technologies sensing attributes and technical limitations of these applications are also shown. Relevant work in this field have also been carried out by the CSIRO Centre in Australia, as seen in [2] and [3] where a review on the progress in the WSN field in the last decade is presented. It introduces several examples of applications in order to show the challenges and difficulties of their deployment. Some of these examples are cattle monitoring, ground water quality, virtual fencing in farms or rain-forest micro-climate monitoring

Related to this work, the University of New England uses in [4] the technology developed by the CSIRO group. Soil sensors and weather stations are used to create a smart farm control portal and so let the farmers develop personalized event descriptions. Some other applications are also found, like in [5], where they propose to monitor health conditions of the vibration screens used by oil sand operators. The main difficulty in this application is the harsh environment where sensors are deployed.

However, real deployments where the network remains working for more than a few months are not very referenced. Some examples have been found related to the monitoring of urban environments. In [6] a ten nodes network is deployed during a year in order to monitor temperature and humidity. Some other deployments in greenhouses can be found in [7],[8] and [9]. Their objective is to measure several environmental parameters to control and maintain desired conditions.

Even though all of these last examples have been carried out, it is still difficult to deploy, test, maintain and debug a complete WSN in a reliable, effective but simple way. This is the main reason why there is a research line focused on covering these challenges, called Test beds for WSNs [10]. The authors in [11] introduce simulation tools for stochastic large-scale sensor network, using multi-object optimization to give users multiple solutions. In [12] some methods are described for deploying WSN under specific indoor environment.

This review shows that, even though there are examples of environmental deployments in the state of the art, it is difficult to find cases showing the problems of real deployments where both network and sensors remain working during long periods.

III. Wireless Sensor Network Platform: Cookies

The Cookies platform has been already presented in many articles and environmental applications like in [13], [14] and [15]. WSN nodes normally require four basic functionalities: wireless communication, data processing, sensing and/or acting, and power supply. In order to have a modular design, the Cookie platform is divided into four different PCBs, each of them covering one of these previous roles. Every layer is connected to the following through a vertical connector as shown in Figure 1. Thanks to this modular design, it is possible to exchange every layer separately permitting quick prototyping and adaptation to new requirements if different sensors, communication modules, power supply sources, etc. are needed. The four layers mentioned are listed below:

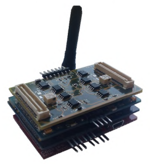

Figure 1: Cookie Node.

1) *Power supply layer*: The node can be powered from a USB cable, lithium or AA batteries or directly from the mains (using the USB connection).
2) *Communication layer*: this layer includes a ZigBee module for wireless communication among nodes.
3) *Processing layer*: this layer includes a low power microcontroller C8051-F930 from Silicon Labs.
4) *Sensor layer*: it includes conditioning circuits for both digital and analogue sensors and/or actuators. This layer changes depending on the sensor used.

IV. ENVIRONMENT DESCRIPTION

The deployments of the sensor networks studied in this work took place in two different scenarios but with the same main goal: a green and real-time monitoring solution for food industry.

A. Meat Treatment Plant

The factory consists of four different areas as seen in Figure 2 with high-level technology and full of automatic processes. A short description of the structure is provided in order to evaluate the proper location of the sensors together with some other issues such as wireless communications and sensor placing, facing several problems caused by the presence of machines and metallic objects.

Figure 2: Meat Treatment Plant: Areas

The environmental measurements took place in different parts of the blue and red areas. The first place was the sewage treatment plant where the water parameters needed to be monitored (Figure 3). The main challenges in this measuring point were the corrosive environment and the sensor soiling, apart from the attenuations caused by metallic objects and the heavy doors of the room. The second important place for monitoring was the washing machines room, where air alkalinity was important for the worker's safety due to the use of detergents.

Figure 3: Meat Treatment Plant. From left to right: Washing Area and water plant

B. Cheese Factory

In this second case, the factory has a larger extension that is not divided in different floors, which hinders the link communication tasks. The factory is divided into four different areas as shown in Figure 4.

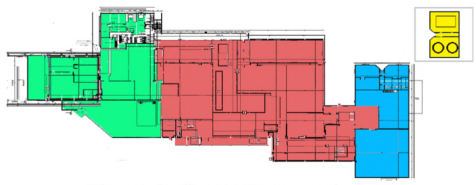

Figure 4: Cheese Factory: Areas

The environmental measurements took place in some distant areas of the factory. The first one, as in the meat factory, was the sewage treatment plant (yellow zone) where water parameters needed to be measured. The main challenge in this case was the distance between the sensors and the coordinator node (COO) that reached more than 120m in open field, apart from the corrosive environment and the sensor soiling. The next important place for monitoring was the maturing room (red zone), where air quality parameters were important for the proper processing of the cheese.

V. DEPLOYMENT ANALISYS

In order to define the features needed for a good quality of communication among nodes, the main parameters have to be presented to understand all the problems encountered during deployments. When it comes to plan the deployment of a WSN, a five-step methodology [16] has been followed. The schematic overview is given in Figure 5.

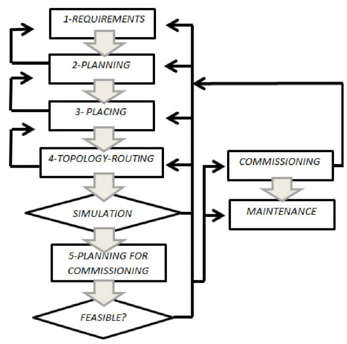

Figure 5: Design Steps

1) *Communication requirements*

- *Quality of communications:* Link quality is extremely important in multi-hop networks to ensure data coverage. Configuring the nodes with the highest transmit power level makes easier the communication but increases the power consumption. For the proposed application, this problem has not been considered since all the routers were plugged to the electricity grid and therefore do not depend on any external battery as sensor devices do. However, it is an aspect that should be taken into consideration in case power supply is not available.

On the other hand, the quality of the signal must be analysed in order to define the maximum reliable coverage distance and therefore to optimize the number of nodes of the WSN. Parameters like *LQI (link quality indicator)* and *RSSI (received signal strength indicator)* help to typify the signal depending on the distance and obstacles found on its way (walls, interferences, etc.). As a result, a good quality signal link has been achieved for 30 m indoor and 80 m outdoor.

- *Data fidelity:* When the sent information is critical either for the proper operation of the production chain, legal parameters bounds, or workers safety, it is required that data reaches the coordinator node without leaks of information. For that reason, packet redundancy and sensor redundancy are needed to guarantee right reception. Redundancy could not be applied in these deployments because sensors were just prototypes and they were not available for redundancy, but it should be accomplished in future industrialized deployments. However, package redundancy was truly put into practice and thanks to it, wrong packets were filtered, more accurate sensor values were obtained by means of the average data obtained, and sensor failures were detected, without forgetting to consider a trade-off between redundancy and consumption.

- *Power Consumption:* A long-lifetime network has been one of the most important requirements on WSNs. The chosen technology has helped to achieve low power consumption thanks to the possibility of configuring the processing and communication layers (explained in Section III) into "Sleep modes" or "zero-consumption configuration" where sensors are not required. In Figure 6 it can be seen that the obtained current consumption during the "Sleep-mode" is close to 70μA (section 1) and it can also be distinguished other two regions that belong to the configuration time (section 2) and transmission time (section 3).The current average obtained in these both regions was 30 mA.

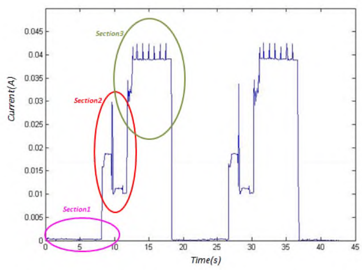

Figure 6: Battery Consumption Profile

The proposed applications do not require continuous monitoring, so only a few measurements per day are taken. It is agreed to take between 5 and 10 measurements every 6 hours in each sensor (see Figure 6). The measuring interval will take about 15-20 seconds, which was enough to take the amount of information needed in those sensors whose establishment time is shorter than 4 s, and despite redundancy. All of this makes possible to estimate the battery life of the nodes (in all of them a 2000 mAh battery and maximum power configuration have been used). *Fault-tolerance:* In order to continue operating properly in case of a failure, maintain communications even when a node fails (battery finishes, breakage, etc.) and be able to continue taking some specific critical measurements in the application environment, the network needs to be robust. In some cases, a very simple solution is using hardware redundancy but always considering a trade-off between fault-tolerance and cost. Furthermore, in case redundancy fails, the software application designed for control and commissioning allows resetting the nodes remotely when a failure occurs and change initial settings regarding sending time and offset values.

2) *Planning*

Planning was based on all different link requirements mentioned above (maximum coverage distance, redundancy nodes, etc.), but also on sensor requirements to achieve the best feasible solution. In Figure 7 an example of a deployment carried out with 10 nodes in a meat factory is shown.

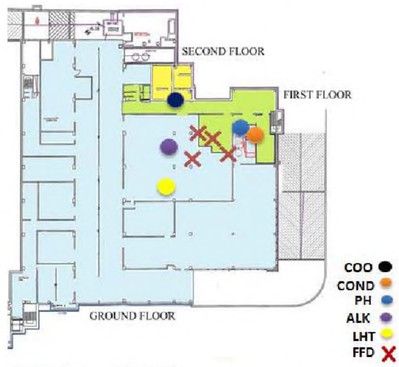

Figure 7: Deployment example

3) *Placing*

In this application, opposite to random deployments [17], a deterministic placement has been used, due to the restrictions of the sensor placing. Starting with the position of the sensor nodes, and measuring the quality of the signal, the router nodes were placed along the way between the sensors and the COO in order to ensure full coverage.

4) *Topology and routing*

A mesh topology has been selected for this application, because of its several advantages. This topology, together with hardware redundancy avoids the collapse of the network if a node is disconnected or it stops working. This topology also allows the addition or removal of nodes from the network easily, which can be useful if other sensors are needed in the future.

5) Commissioning:

In order to manage different aspects of the WSN remotely, a software application has been developed. These applications allows to not only monitor the information provided by the sensors in real time, but also configure the end-devices sleep time and measuring intervals or reset the nodes if several failures are detected.

VI. PROBLEM OVERVIEW

Environmental WSN deployments present several challenges apart from the traditional routing problems and communications dependability. In general, they are deployed in environments where human interaction is more than likely so they must be unobtrusive and reliable. At the same time, the most important thing for a factory is that its production chain is never interrupted so nodes must be kept out of this line at all times. Because of that, sometimes nodes need to be placed in not accessible locations so reliability and ultra-low power are obligatory in order to ensure as low maintenance as possible during long periods.

The growing concern about environmental problems and their importance in the food industry as an important source of environmental impacts favours the will of many food factories to monitor and control their emissions. In order to achieve this goal, the environmental consequences of the production processes need to be determined. The Life Cycle Assessment (LCA) methodology allows identifying the consequences of the life cycle of a product in the environment. This is done evaluating the potential environmental impacts over the production chain (ISO 14040, 2006). According to this methodology and considering factory requirements, several environmental indicators were introduced as relevant in the initial stages of this work. These parameters are ion concentrations of P, NH_4^+ and Cl^-, turbidity, total suspended solids, pH, BOD_5, COD, CO_2 and ammonia.

After the study of the environmental parameters mentioned before, some of them needed to be discarded due to their high price, maintainability and power consumption. As an example of these problems, the ion concentration measurement could not be carried out easily, in an unattended way, due to the need of adding reactive solutions. The turbidity measurement uses an optical sensor with high power consumption and high cost, or the BOD_5 measurement needs to keep a water sample under very specific conditions (complete darkness and 20ºC) during 5 days, which requires a complex mechanical system that makes the measurement unaffordable.

Commercial sensors are usually designed for laboratory purposes and therefore, their features are limited. Frequent recalibration, pure water samples or limited temperature and humidity ranges are some examples of conditions difficult to achieve in an on-field application. Therefore, working conditions in the deployment need to be taken into account in the sensor selection process. Once all these limitations are considered, those sensors that overcome these problems were selected in order to monitor the following environmental parameters: conductivity, pH, temperature of the water, CO_2, NH_3 and pH of the air.

The sensor used to measure these parameters as well as the problems that appear during their deployment are explained in detail in the next lines.

Water Quality Nodes: pH, Conductivity and Temperature

pH is one of the most important parameters related to waste water quality. This parameter indicates if the treatment process is being carried out correctly and it is crucial since some chemical processes only take place under certain pH ranges. For instance, some chloride reactions only occur when pH is within 6.5 and 8 units. Conductivity is also a very representative parameter since it measures the ion activity in the wastewater.

The nodes presented in this work, shown in Figure 8, include the pH and conductivity sensors together with a temperature sensor. Measuring temperature is not only important to know more information about the state of the wastewater but also because pH and conductivity depends on the temperature value. In order to adjust the measurements to this variation, a 4-wired pt100 is also included in these probes.

Figure 8: Water Nodes

The problems encountered when designing and deploying these nodes are regarding sensor selection (robustness, calibration, price and adaptability) and sensor placing (climate conditions, interaction with workers and cleaners, sensor soiling, production chain interaction).

The selected sensor for the pH measurement is an Isfet probe. It is an experimental-state sensor with a price of 120 € which is six times cheaper than a commercial ISE probe. Since the sensor is still in a research state, the casing needed to be specially designed by the authors as shown in Figure 8. Apart from a plastic case, a floating filter needed to be added to the solution to avoid sensor soiling since the wastewater contained mud and suspended solids.

In the case of the conductivity measurement, the same limitations as in the previous were found. Finally, the chosen solution was a 4-Platinum-electrode probe. As it happened with the pH sensor, this one is also in a research state so the same casing and filter were used. The selected probe presents several advantages such as low cost (100 €), accuracy and adaptability to the Cookies platform.

During the deployment of the network, these sensors were installed in the wastewater treatment plant of both factories (Figure 9). Some problems were presented during this process. In the case of the cheese factory, the distance between this location and the rest of the network was long enough (150 m) so the addition of some router nodes along the way was needed. The possibility of water reaching the electronic system since the nodes were placed in a basin outdoors required closing it appropriately and the presence of organic material on the surface of the water forced to include a fabric filter covering the sensor.

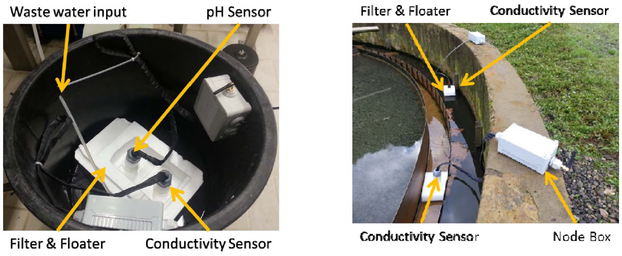

Figure 9: From left to right: Water Nodes in the meat factory and water nodes in the cheese factory.

- *Alkalinity: pH of the Air*

The original parameter required by the application was the alkalinity of the air given by the concentration of sodium oxide. Since measuring the concentration of sodium oxide present in the air is not an easy task, an indirect measurement of the pH of the air was proposed and accepted. The Na_2O in the air that reacts with the water steam creates sodium hydroxide and therefore favours a basic environment.

The sensor used in this application is an optic sensor consisting of a piece of glass covered with a special coating. This coating is made of an organic compound (3, 3-dichlorophenolsulfonephthalein) that changes its colour depending on the pH of the air. In order to measure the changes in the colour of the glass, a colorimeter is included in the node.

Since the sensor consists of a glass, it is very important to place the node in a location were the steam coming from the washing machines does not fogged up the crystal, see Figure 10. Besides, the node is also measuring humidity, so in the case of finding an abnormal humidity value, it is possible that the alkalinity value cannot be trusted.

Figure 10: Node Placing: pH of the Air

- *Ammonia and humidity Node*

The measured of this parameter is needed in the cheese factory due to the high concentrations of ammonia in the maturing rooms. At the beginning, the selected sensor to measure ammonia concentration was a three-electrode electrochemical sensor from the company Alphasense (NH3-B1) [18]. The main problem found with this sensor was its behaviour in atmospheres of extremely high relative humidity (RH). In environments of more than 90% of RH, such as the one where the network was deployed (around 96%), or with less than 15%, the sensor starts leaking, and thus, it suffers an irreparable damage.

Regarding this specific application, the RH encountered oscillates between values of 40% and reaching the highest ones of even 98%. Due to this, a contingency plan needed to be carried out to assure the proper operation of the sensor.

The first idea to solve the humidity problem was isolating the sensor case from the environment using electro valves or airtight door locks. These valves could be controlled and opened automatically while controlling the inner RH of the case with a desiccant such as Silica Gel, using the right amount to keep humidity under 60% (which is the optimum RH for this sensor). The problem using this method is the complexity of the solution, the increment in the final price and the increase of power consumption.

After analysing other sensors and set ups, the best option was calculating the ammonia concentration in an indirect way taking advantage of one of the sensors that were already developed for the same deployment, the alkalinity sensor shown in Figure 10.

Figure 11: Node Placing: Initial Ammonia node

Assuming that ammonia is the only or the most relevant chemical specie that affects the pH value of a certain air volume, it is possible to calculate the ammonia concentration by measuring the pH of the air. It is important to highlight that the accuracy of the measurement is highly dependent on the air volume. If the volume is too big, in order to obtain a most accurate value, the best way is using several sensors in different places so that different concentrations can be calculated and then show an average value.

After previous considerations, the formulae to obtain the concentration of ammonia from the pH value are the following:

$$pH = X \quad [H^+] = 10^{-X}$$

$$[H_3O^+][OH^-] = 10^{-14} \rightarrow [OH^-] = 10^{-14-(-X)}$$

Equilibrium Reactions: $NH_3 + H_2O \leftrightarrow NH_4^+ + OH^-$

Initial: $[NH_3] : Co\ (molar\ concentration)$

Equilibrium: $[NH_3] = Co - 1.995 \times 10^{-5}$

$$[NH_4^+] = [OH^-] = 10^{-14-(-X)}$$

$$Kb = 1.8 \times 10^{-5} = \frac{([NH_4^+] \times [OH^-])}{[NH_3]} = \frac{(10^{-14-(-X)}) * (10^{-14-(-X)})}{Co - 1.995 \times 10^{-5}}$$

$$Co = \frac{\left((10^{-14-(-X)})^2\right) + \left((10^{-14-(-X)}) \times Kb\right)}{Kb}$$

To obtain it in ppm:

$$Co(ppm) = 1.66 \times 10^{-18} \times 0.0082 \times (273 + T) \times 6.023 \times 10^{23} \times Co[NH_3] = Co - 1.995 \times 10^{-5}$$

Even though, this is a theoretical approach to obtain the ammonia concentration, comparing the results with the real values showed that this method was appropriate.

- *Carbon Dioxide Node*

In order to measure the carbon dioxide concentration, a potentiometric solid-state sensor from the company Alphasense (CO2-D1) [18], was selected.

Related to environmental issues, this sensor encounters the same problems mentioned above for the NH_3 sensor, and thus, a similar solution is advised. In this case, however, since there is no possibility to do an indirect measure, the option applied is the measurement using an isolated and controlled atmosphere of RH (60%) with Silica Gel.

In order to measure the CO_2 concentration in a proper way, some requirements such as having a parallel flow of air of 9 l/min, which was achieved through an electric miniature fan, having a different output diameter area than the input one and having a minimum dead volume of air above sensor, needed to be taken into account. Under laboratory conditions, after the calibration, the sensor worked properly and gave out the expected measurements, but, due to the high RH of the factory where it was working, the sensor started to lose functionality and reached a point where it no longer gave out reasonable values.

Due to all these previous reasons, this node was not used in the final deployment.

VII. CONCLUSIONS

In this work, two real deployments in food factories have been presented.

The application is in the field of environmental monitoring and the problems related to this have been studied and solved.

Several prototypes for different parameters have been developed, considering the special requirements of the WSN technology, with promising results. This has implied the inclusion of sensors that are not usual in the WSN traditional applications, and the results have been very satisfactory.

A state-of-the-art deployment methodology has been followed to determine the node location, network topology and commissioning and maintenance issues among others. The sensor network was deployed for testing during two months.